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Optimization of pulsed electric fields-assisted thawing process conditions and its effect on the quality of Zhijiang duck meat

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ABSTRACT

Freezing storage is a common preservation method for industrialized duck meat. However, both the frozen storage and thawing processes of meat can affect meat quality. Therefore, appropriate thawing methods are crucial for maintaining good meat quality. In this study, a pulsed electric field (PEF) was used for thawing zhijiang duck meat and the freshed duck meats were used as control. Optimization of the PEF-assisted thawing process and its effect on the quality of zhijiang duck meat were analyzed. Our data showed that the shear force in the 2 kV/cm PEF-assisted thawing group was the lowest in PEF-assisted thawing groups. The color of zhijiang duck meat in the 2 kV/cm PEF-assisted thawing group was optimal. The 2 kV/cm PEF-assisted thawing could improve the texture characteristics of zhijiang duck meat and enhance water holding capacity of zhijiang duck meat. PEF-assisted thawing could better maintain the microstructure of zhijiang duck meat. Our data showed that if the intensity or duration of PEF treatment is too high, the quality of duck meat will actually decrease. Therefore, appropriate parameters should be selected in practical applications, which will provide a reference for the application of PEF-assisted thawing on the market.

1. Introduction

China is the world's largest producer of duck meat, accounting for approximately 70 % of the world's production. Statistics show that the total output value of meat ducks was 120.307 billion yuan in 2022. Duck meat is the third most consumed meat in China. There are many kinds of wild ducks in the world, among which *Anas platyrhynchos* and *Anas poecilorhyncha* are recognized as the ancestors of domestic ducks(Tarana et al., 2023). *Anas platyrhynchos* are widely distributed in Eurasia and northwest America, while *Anas poecilorhyncha* is mainly distributed in Asia(Moselhy & Hady, 2019; Y. Zhang et al., 2023). Zhijiang duck is made into famous dishes in zhijiang city in Hunan Province. During the Mid-Autumn Festival and the Double Ninth Festival, people in zhijiang will eat this duck meat, and the consumption of this duck meat become a custom that has been around since the Yuan Dynasty.

Freezing storage is a common preservation method for industrialized duck meat(Leygonie, Britz, & Hoffman, 2011). However, both the frozen storage and thawing process of meat may affect the meat qualities, including decreased water retention, loose tissue structure, fat oxidation and protein oxidation(Alvarenga, Hopkins, Ramos, Almeida, & Geesink, 2019; Jia, Sha, Meng, & Liu, 2019; Xia, Kong, Liu, Diao, & Liu, 2012). At present, the thawing technology of meat mainly includes air thawing (Luyun Cai, Zhang, Cao, & Cao, 2020), hydrolysis thawing(Eastridge & Bowker, 2011), refrigerator thawing(Ersoy, Aksan, & Ozeren, 2008; Xia et al., 2012), microwave thawing(Cao et al., 2018), ultrasonic thawing technology, and ultra-high pressure thawing(L. Cai, Cao, Regenstein, & Cao, 2019). Each thawing technique has advantages and disadvantages. For example, the natural thawing time is long, which can easily cause a quality decline. Hydrolysed freezing can easily cause poor color and flavor. Refrigerator thawing will result in low efficiency and large juice loss. Ultrahigh-pressure thawing equipment is expensive and requires high energy consumption. Therefore, it is imperative to explore new techniques for thawing duck meat.

Pulsed electric field (PEF) is a method of utilizing high intensity (0.1–40 kV/cm) and narrow pulse width (0–100 μs) combined with high-frequency (0–2000 Hz) high-voltage pulse electricity(Bhat,

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Morton, Mason, & Bekhit, 2019; S. Zhang, Sun, Ju, Bao, Zeng, & Lin, 2021). This new non-thermal processing technology for food has the advantages of being fast and efficient, having low power consumption, and producing low pollution(S. Zhang, Sun, Ju, Bao, & Lin, 2021). Recently, research has demonstrated that PEF treatment has the potential to enhance the thawing rate, inhibit the growth of microorganisms, regulate enzyme activity, and facilitate energy transfer(Xie et al., 2021). It also has been found to improve the tenderness of various types of meat, such as beef, chicken, lamb, and pork, while also indirectly influencing the pH value and color of the meat(Hsieh, Lai, Ho, Huang, & Ko, 2010; Jia et al., 2019). In addition to improving the tenderness, PEF also reduces the fatty acid content and increases the amino acid content of frozen lamb, as well as increases the salt diffusion rate during pork pickling(Arroyo et al., 2015; Astrain-Redin, Raso, Cebrian, & Alvarez, 2019; Kantono, Hamid, Ma, Oey, & Farouk, 2021). PEF may also decrease the quality of duck meat decrease during assisted thawing, which significantly accelerates the drying of food and may cause food to produce odors and spoil. Therefore, appropriate parameters should be selected in practical applications.

Our research aims to find the best way to thaw zhijiang duck meat, providing reference for the storage and thawing of other duck meat. In this study, PEF was used for thawing zhijiang duck meat, and its effect on the thawing time, shear force, color, texture, fat oxidation value, and muscle fibre structure were measured to optimize the PEF thawing process conditions. Our data could serve as a valuable point of reference for the application of PEF-assisted thawing on the market.

2. Materials and methods

2.1. Materials and reagents

The ducks were obtained from the Mingyou Food Co., Ltd. at Zhijiang District in the city of Huaihua with about 4 months age and 3 kg. Ethylenediaminetetraacetic acid (EDTA) was purchased from China National Pharmaceutical Group Chemical Reagent Co., Ltd. Thiobarbital acid was obtained from China National Pharmaceutical Group Chemical Reagent Co., Ltd. A protein carbonyl content detection kit (BC1275) and total sulfhydryl content detection kit (BC1375) were purchased from Beijing Solarbio Biotechnology Co., Ltd. Potassium bromide was obtained from China National Pharmaceutical Group Chemical Reagent Co., Ltd. 2.5 % glutaraldehyde was obtained from China National Pharmaceutical Group Chemical Reagent Co., Ltd.

2.2. Instruments

The digital display constant-temperature water bath (HH-S) was obtained from Jiangsu Kexi Instrument Co., Ltd. The electronic analytical balance (ATX224) was purchased from Zhejiang Hengyue Instrument Co., Ltd. The spectrophotometer (CS-580 A) was from Hangzhou Caipu Technology Co., Ltd. The meat tenderness tester (RH-N50) was obtained from Guangzhou Runhu Instrument Co., Ltd. The texture analyser (TA. XTplus) was purchased from SMS Limited in the United Kingdom. The full wavelength enzyme-linked immunosorbent assay (1510) was from Thermo Fisher Scientific Co., Ltd. The low field nuclear magnetic resonance imaging and analysis system (NMI20-060 V-I) was obtained from Suzhou Newman Analytical Instruments Co., Ltd. The camera microscope (ECLIPSE-Ci) was purchased from Nikon Corporation, and the scanner (SCAN II) was purchased from Jinan Danjier Electronics Co., Ltd. The scanning electron microscope (SEM) (JSM-6380LV) was purchased from Japan Electronics (JEOL) Co., Ltd. The pulsed electric field equipment was obtained from the School of Food Science and Engineering, South China University of Technology, China. Pulse electric field equipment (PEF-EX-1900) was developed by South China University of Technology in China, with an automatic discharge point processing device that can control the number of pulse electric field treatments, 600 mL process volumn and width of 40 μs exponential attenuation wave. Circular dichroism analyser (MOS-500) was from BIO-LOGIC Science Instruments SAS.

2.3. Pulse electric field-assisted thawing

The ducks were obtained from the Zhijiang District in the city of Huaihua with about 4 months age and 3 kg. And the fresh duck meats were cutted into small pieces (5.0 cm × 5.0 cm × 2 cm) immediately after being slaughted within 1 h. Then, the packaged samples were stored in self-sealing bags and frozen at −20 °C for 48 h. The experimental groups were thawed with pulsed electric fields of 0, 1, 2, 3, and 4 kV/cm by rotating the button to fix the electric field. Both groups were thawed at the same temperature (20 ± 1 °C). The sterilized TP101 probe type thermometer was inserted into the centra of the duck breast meat by hands. The samples were stored in 4 °C refrigerator, and subsequent analysis was conducted once thawing with the same temperature at the centra of the duck breast meat. The frequency (f) was from 0 to 10^3 Hz.

2.4. pH tests

The pH of the duck breast after being thawed was measured using a handheld pH meter. Each group was analyzed at least three times in different locations on each sample and then averaged.

2.5. Cooking loss rate

The PEF-thawing samples were cut into 4 × 4 × 1 cm pieces. The weight was recorded as m1 in the cooking bag. A digital thermometer was inserted into the centra of the meat sample, and the meat sample was then placed in a water bath at 80 °C. Once the central temperature of the meat sample reached 70 °C, the sample was rapidly cooled to room temperature using tap water. The surface moisture was removed using filter paper, and the weight was recorded as m2. The cooking loss rate could be calculated using the formula: (m1 - m2)/m1 × 100 %.

2.6. Shear force

Shear force refers to the force used by the cutting tool of the testing instrument to cut through the meat sample. The meat samples were cut with a diameter of 1.27 cm, and the shear force value was measured by the RH-N50 meat tenderness tester.

2.7. Meat color

Meat color refers to a comprehensive optical characteristic of the content, oxidation/oxidation status, and distribution of myoglobin in muscles. The brightness value L*, the redness value a* and the yellowness value b* of the thawed duck breasts were measured by the spectrophotometer.

2.8. Meat texture

The samples were cut into small pieces of 2 cm × 2 cm × 1 cm, and their texture characteristics were measured with a food performance tester, with 6 parallel samples in each group. The parameters were set as follows: compression ratio of 50 %, pretest speed of 2 mm/s, test rate of 1 mm/s, return rate of 1 mm/s, trigger point load of 5 g, and probe of P/36R.

2.9. The lateral relaxation, distribution and fluidity of water in duck breast

The duck breast was heated at 35 °C for 30 min. Then, the sample was cut into 1.5 cm × 1.5 cm × 2 cm pieces and placed at the bottom of a 40 mm nuclear magnetic resonance tube, and the lateral relaxation characteristics of duck breast samples were analyzed using the NMI20-

060 V-I nuclear magnetic resonance analyser.

The NMI20-060 V-I nuclear magnetic resonance analyser was utilized to conduct nuclear magnetic resonance imaging on duck breast samples. The temperature during the test was set at 35 °C, and the instrument was preheated for 30 min. Before the sample was tested, a standard oil sample was used for calibration. The main imaging parameters were TR of 500, TE of 20, and AVERAGES of 4, with an imaging size of 40 × 40 mm. Then, the images were obtained.

2.10. Lipid peroxide value

The 10 g sample was chopped and placed in a test tube. Next, 50 mL of a 7.5 % trichloroacetic acid solution containing 0.1 % EDTA was added. The mixture was shaken for approximately 30 min. The liquid was then filtered twice using a double layer filter paper. Next, 5 mL of the supernatant was mixed with 0.02 mo1/L 2-thiobarbituric acid solution. This mixture was placed in a water bath for 40 min at room temperature and centrifuged at a speed of 10,000 r/min for 10 min. The supernatant was collected, and 5 mL of chloroform was added. After, the absorbance of the supernatant was measured and recorded, and the TBARS value was calculated using the following equation: TBARS (mg/100 g) = (A532-A600)÷155 × 72.6 × 10.

2.11. Carbonyl content and total sulfhydryl content

1 g duck meats were minced and the 10 mL pH 7.4 phosphate buffer is added. Then, the mixture was homogenized at 15000 rpm for three times. The homogenate were transferred into a 10 mL centrifuge tube and 12,000 *g* centrifuged for 5 min at 4 °C. Then, the supernatant was taken as sample. 1 mL supernatant and 4 mL 2, 4-dinitrophenylhydrazine hydrochloride guanidine solution were mixed and placed in dark place at 37 °C for 30 mins. The mixture is 12,000 rpm centrifuged for 10 mins after 5 mL 20 % trichloroacetic acid being added. Precipitates are collected.

10 mL anhydrous ethanol ethyl acetate solution (1:1) is used. Then, the precipitates are washed 4 times after the 10 mL anhydrous ethanol ethyl acetate solution being added. After adding 12 mL of guanidine hydrochloride solution, the mixture is taken a water bath at 37 °C for 15 mins. The supernatant is collected after the mixture being centrifugated for 15 mins. For the test of carbonyl content. The absorbance value of the supernatant is measured at 370 nm with spectrophotometer. The carbonyl content is calculated using a molar absorption coefficient of 22,000 L/(moL• cm). For the test of total thiol groups. 1 mL supernatant is added in the 8 mL pH 8.0 Tris glycine buffer (10 mM EDTA, 0.2 M Tris HCl, 8 M urea). The supernatant is collected after being centrifuged for 2 mins. Then, the 0.5 mL pH 8.0 ellmans reagent (0.1 M Tris glycine buffer, 10 mM DTNB) is added in 4.5 mL supernatant after being transfered into a centrifuge tube and stewing 25 °C for 30 mins. The absorbance value of the supernatant is measure at 412 nm with spectrophotometer. And the total thiol content is calculated using an extinction coefficient of 13,600 /(moL• cm).

2.12. Protein secondary structure

The secondary structure of duck meats was tested using a circular dichroism spectrometer. It utilizes the absorption characteristics of amino acids such as tryptophan, tyrosine, and phenylalanine in proteins to determine the secondary structure of proteins by measuring the difference in absorption between left-handed and right-handed circularly polarized light. Briefly, the samples were diluted to 0.2 mg/mL, and the parameters were setted as follows: 200–260 nm scanning wavelength range, 120 nm/min scanning speed. Each sample was scanned 3 times. The secondary structure composition was evaluated on the basis of far-UV CD spectra. Data was analyzed using Chirascan software. And the relative content of the corresponding conformation was calculated using CD neural network (CDNN) software.

2.13. The microstructure of muscle fibres in Zhijiang duck meat

The hematoxylin eosin (HE) staining procedure was conducted as follows: frozen sections were placed in distilled water for 2 min, followed by staining with hematoxylin staining solution for 5 min. The excess staining solution was rinsed with water for 10 min, and then the sections were washed again with distilled water. Dehydration was carried out using 95 % ethanol for 5 s, followed by staining with eosin staining solution for 30 s. Further dehydration was performed using 95 % ethanol for 2 min, followed by replacement with fresh 95 % ethanol for 2 min. Finally, the sections were made transparent in xylene for 5 min, and images were obtained using microscopy.

The microstructure of duck breast samples was analyzed using a scanning electron microscope (SEM). The samples were cut into approximately 2 mm × 2 mm × 2 mm cubes and soaked overnight in a 2.5 % glutaraldehyde solution with a pH of 6.8. Subsequently, the samples were dehydrated in 50 %, 70 %, 80 %, 90 %, and 100 % ethanol for 15 min. Then, the samples were stored in a sealed container and installed on a bronze short handle and coated with a layer of gold. SEM was used to obtain the microstructure of duck breast meat after the samples were coated with a layer of gold.

2.14. Statistical analysis

The Origin8.0 software and IBM SPSS Statistics 23 software were used for data statistics. Different lowercase letters indicated $P < 0.05$. Each group has at least 5–8 replicates. Each group of experiments was measured three times, and the results were represented as “mean ± standard deviation”.

3. Results

3.1. Effect of PEF-assisted thawing on the quality of Zhijiang duck meat

The thawing times, pH, cooking loss rates, and shear force of zhijiang duck meats were measured after the frozen zhijiang duck meats were thawed by PEF-assisted thawing. The results showed that the total defrosting time of zhijiang duck meat was 96, 14, 12, 10 or 8 min under intensities of 0, 1, 2, 3 or 4 kV/cm PEF-assisted thawing, respectively. The pH in the thawed zhijiang duck meat without PEF-assisted thawing group was 6.18. The pH values were 5.89, 6.12, 6.18 and 6.26 in the 1, 2, 3 and 4 kV/cm PEF-assisted thawing groups, respectively. The cooking loss rate was 17.87 ± 0.12 in the 0 kV/cm PEF-assisted thawing group. The cooking loss rates were 18.19 ± 0.54, 13.94 ± 0.96, 15.54 ± 0.52 and 19.39 ± 0.75 in the 1, 2, 3 and 4 kV/cm PEF-assisted thawing groups, respectively; these values were significantly different from the control group. The shear force was 24.92 ± 0.20 in the 0 kV/cm PEF-assisted thawing group. The shear force was 15.36 ± 0.39, 10.04 ± 0.24, 13.65 ± 0.43 or 14.92 ± 0.59 in the 1, 2, 3 or 4 kV/cm PEF-assisted thawing group, respectively. Based on these data, a higher electric field intensity correlated to a shorter thawing time and higher pH of zhijiang duck meat. The shear force in the 2 kV/cm PEF-assisted thawing group was the lowest (Table 1).

3.2. Test the color of Zhijing duck meat

The color of meat products directly affects the consumption desire of consumers and is one of the key indicators of the quality of meat products. L*, a* or b* are the brightness value, redness value or yellow value, respectively. Within a certain range, a larger L* value correlates to a better gloss of the sample; a larger the a* value correlates to a better meat color. A higher b* value correlates to less fresh meat. As shown in Table 2, the L*, a* or b* values of control samples were 46.15 ± 0.47a, 10.86 ± 0.23a and 9.11 ± 0.22c. The L* value in the 2 kV/cm PEF-assisted thawing group was significantly higher than the control L* value, but no evident difference was observed between the 1 or 3 kV/cm

Table 1
Effects of PEF treatment on the quality of duck meat.

Treatment	Thawing time (min)	pH value	Cooking loss (%)	Shear force (N)
Control		5.82 ± 0.021e	12.98 ± 0.87e	9.78 ± 0.68e
0 kV/cm	96	6.18 ± 0.043c	17.87 ± 0.12c	24.92 ± 0.20a
1 kV/cm	14	5.89 ± 0.025d	18.19 ± 0.54b	15.36 ± 0.39c
2 kV/cm	12	6.12 ± 0.035b	13.94 ± 0.96e	10.04 ± 0.24e
3 kV/cm	10	6.18 ± 0.015c	15.54 ± 0.52d	13.65 ± 0.43d
4 kV/cm	8	6.26 ± 0.015a	19.39 ± 0.75a	14.92 ± 0.59c

Note: Different lowercase letters indicated $P < 0.05$. The fresh meats were used as control. Each group has at least 5–8 replicates.

Table 2
Effects of PEF treatments on the color of duck meat.

Treatment	L*	a*	b*
Control	46.15 ± 0.47a	10.86 ± 0.23a	9.11 ± 0.22c
0 kV/cm	44.96 ± 0.76c	9.56 ± 0.15a	10.22 ± 0.12b
1 kV/cm	45.38 ± 0.23b	10.47 ± 0.23a	9.26 ± 0.24c
2 kV/cm	45.94 ± 0.35a	10.46 ± 0.29a	9.20 ± 0.14c
3 kV/cm	45.26 ± 0.56b	10.26 ± 0.31a	9.27 ± 0.27c
4 kV/cm	44.20 ± 0.27d	9.94 ± 0.26b	10.82 ± 0.22a

Note: Different lowercase letters indicated $P < 0.05$. The fresh meats were used as control. Each group has at least 5–8 replicates.

PEF-assisted thawing group and the control group. The a* value was 9.56 ± 0.15 in the 0 kV/cm PEF-assisted thawing group. The a* values were 15.36 ± 0.39, 10.04 ± 0.24, 13.65 ± 0.43 and 14.92 ± 0.59 in the 1, 2, 3 and 4 kV/cm PEF-assisted thawing groups, respectively. The b* value was 10.22 ± 0.12 in the control group. The b* value was 10.82 ± 0.22 in the 4 kV/cm PEF-assisted thawing group. No significant difference between the PEF-assisted thawing groups was observed. Based on these data, the color of zhijiang duck meat in the 2 kV/cm PEF-assisted thawing group was optimal.

3.3. Zhijiang duck meat texture test

The effect of PEF-assisted thawing on the texture of zhijiang duck meat, including hardness, chewability, cohesiveness, and elasticity, is provided in Table 3. In the 0 kV/cm PEF-assisted thawing group, the hardness was 115.47 ± 15.74. The hardness values were 103.73 ± 8.79, 79.70 ± 5.99, 90.49 ± 5.31, and 127.43 ± 4.44 in the 1, 2, 3, and 4 kV/cm PEF-assisted thawing groups, respectively. Notably, the hardness in the 2 kV/cm PEF-assisted thawing group was significantly lower than that in the other groups. Furthermore, the chewiness of the 2 kV/cm PEF-assisted thawing group was also lower than that of the control groups, with a significant difference observed between the 1 and 2 kV/cm PEF-assisted thawing groups. The elasticity of the 0 kV/cm PEF-assisted thawing group was measured to be 1.93 ± 0.13. In the PEF-assisted thawing groups, the springiness values were 2.40 ± 0.22, 3.21 ± 0.31, 2.87 ± 0.031, and 3.08 ± 0.087, respectively. Notably, the elasticity in the 2 kV/cm PEF-assisted thawing group was highest. Based on these results, the 2 kV/cm PEF-assisted thawing has the potential to enhance the texture characteristics of zhijiang duck meat.

Table 3
Effects of PEF treatment on texture of duck meat.

Treatment	Hardness (N)	Springiness	Chewiness (N)	Cohesiveness
Control	68.62 ± 3.78f	2.97 ± 0.18ab	62.95 ± 2.88e	0.31 ± 0.049b
0 kV/cm	115.47 ± 15.74ab	1.93 ± 0.13b	115.07 ± 6.05b	0.34 ± 0.051b
1 kV/cm	103.73 ± 8.79bc	2.40 ± 0.22b	76.53 ± 3.26c	0.37 ± 0.058b
2 kV/cm	79.70 ± 5.99d	3.21 ± 0.31a	79.80 ± 1.68c	0.40 ± 0.020ab
3 kV/cm	90.49 ± 5.31 cd	2.87 ± 0.031a	105.90 ± 4.19b	0.43 ± 0.058ab
4 kV/cm	127.43 ± 4.44a	3.08 ± 0.087a	133.57 ± 11.16a	0.47 ± 0.058a

Note: Different lowercase letters indicated $P < 0.05$. The fresh meats were used as control. Each group has at least 5–8 replicates.

3.4. Effect of PEF on the melting and loss of immobilized water of Zhijiang duck meat

Low field nuclear magnetic resonance (LF-NMR) is a highly effective method for assessing the distribution and fluidity of water in muscles(Hu et al., 2021). In LF-NMR, three distinct forms of water in muscles are measured: T21 (0.1–10 ms), T22 (10–100 ms), and T23 (100–1000 ms) (Y. He et al., 2023). The relative percentages of these three types of water including bound water, trapped water, and free water in pulsed electric field-assisted thawing muscles (P21, P22, P23) are listed in Table 4. Control samples present the highest P21 value. The P21 value of the PEF-thawing groups at 1, 2, or 3 kV/cm was higher (3.64 % ± 0.047 %, 3.68 % ± 0.010 %, and 3.61 % ± 0.040 %, respectively) than that of the 0 kV/cm PEF-assisted thawing group (2.97 % ± 0.015 %). The P21 values were highest at 2 kV/cm (3.68 % ± 0.010 %), and no significant differences were observed between the 1 and 3 kV/cm PEF-thawing groups. Control samples present the highest P22 value. The percentage of bound water (P22 values) in the PEF-thawing groups at 1, 2, and 3 kV/cm (94.40 % ± 0.10 %, 95.58 % ± 0.099 %, and 95.10 % ± 0.083 %, respectively) was also higher than that in the 0 kV/cm PEF-assisted thawing group (93.55 % ± 0.28 %). Among the groups, the voltage of 2 kV/cm group showed the greatest P22 values (95.58 % ± 0.099 %). However, the P23 values represented the proportion of mobile water, the P23 value of control samples is the lowest (0.23 % ± 0.071 %) and the P23 in the PEF-assisted thawing groups with voltages of 1, 2, and 3 kV/cm (0.25 % ± 0.022 %, 0.26 % ± 0.085 %, and 0.29 % ± 0.011 %, respectively) were significantly lower than those in the 0 kV/cm PEF-assisted thawing group (1.35 % ± 0.027 %). Notably, the P21 and P22 values were higher in the 2 kV/cm PEF-assisted thawing group which closed to the value of fresh meat group. The visualization of water distribution and movement within thawed muscle was obtained via MRI, as shown in Fig. 1B. Red and blue hues in the figure correspond to higher and lower H-proton density, respectively, showing the water content within the muscle tissue(Z. Zhang, Yang, Zhou, Zhang, & Wang, 2017). Upon comparing the 0 kV/cm PEF-assisted thawing group to the PEF-thawed samples, the 0 kV/cm PEF-assisted thawing group evidently exhibited a larger blue region, whereas the PEF-thawed samples showed larger red regions. In particular, the muscle fibre arrangement in the 2 kV/cm PEF-thawed samples demonstrated a greater presence of bound water. These findings indicated that PEF-facilitated thawing at 2 kV/cm accelerated the thawing process of ice crystals and diminished the loss of

Table 4
P21, P22 and P23 of duck meat (P21, P22 and P23 represent the percentages of bound water, immobile water and free water, respectively).

Treatment	P21(%)	P22(%)	P23(%)
Control	3.71 ± 0.067a	95.79 ± 0.14a	0.23 ± 0.071d
0 kV/cm	2.97 ± 0.015d	93.55 ± 0.28d	1.35 ± 0.027a
1 kV/cm	3.64 ± 0.047ab	94.40 ± 0.10c	0.25 ± 0.022d
2 kV/cm	3.68 ± 0.010a	95.58 ± 0.099a	0.26 ± 0.085d
3 kV/cm	3.61 ± 0.040b	95.10 ± 0.083b	0.29 ± 0.011c
4 kV/cm	3.51 ± 0.021c	94.65 ± 0.16c	0.95 ± 0.023b

Note: Different lowercase letters indicated $P < 0.05$. The fresh meats were use as control. Each group has at least 5–8 replicates.

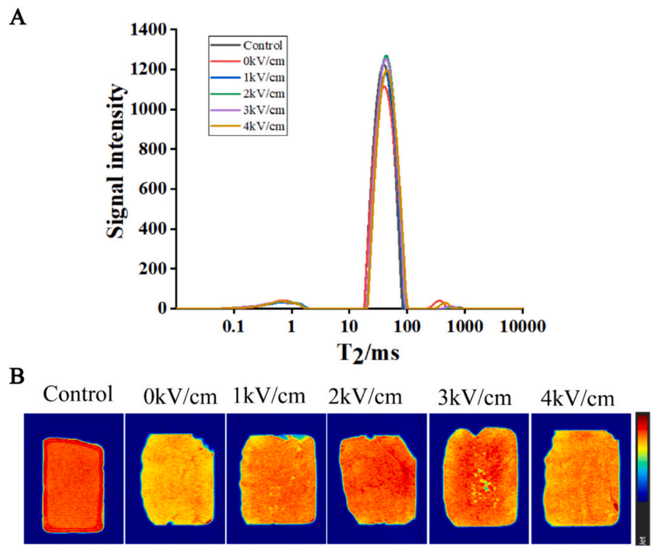

Fig. 1. Effect of PEF treatment on water migration and distribution in duck meat. (A) The thawed duck breast meats were treated with 0,1,2,3 and 4 kV/cm PEF and then, the water migration was tested by the Low Frequency- Nuclear Magnetic Resonance(LF-NMR) T2 relaxation time was measured from 0 to 10,000 ms and (B) The duck breast meats were treated with 0,1, 2, 3 and 4 KV/cm PEF and then, the water distribution was tested by the method of Nuclear Magnetic Resonance Imaging (MRI). The fresh meats were use as control.

bound water and trapped water.

3.5. Effect of the 2 kV/cm PEF-assisted thawing on the oxidation of fat and protein in Zhijiang duck meat

As shown in Fig. 2, the minimum TBARS value of control samples, the thiobarbituric acid values were measured as 0.096 ± 0.027, 0.11 ± 0.0058, 0.13 ± 0.0058, 0.19 ± 0.010, or 0.23 ± 0.012 mg/100 g in the 0, 1, 2, 3, or 4 kV/cm PEF-assisted thawing groups, respectively. No significant difference was observed between the control, 1, and 2 kV/cm PEF-assisted thawing groups. However, the 4 kV/cm PEF-assisted thawing group exhibited the highest thiobarbituric acid values. The carbonyl values were measured as 0.030 ± 0.0021, 0.032 ± 0.0025, 0.034 ± 0.0015, 0.040 ± 0.0027, or 0.061 ± 0.0031 μmol/g in the 0, 1, 2, 3, or 4 kV/cm PEF-assisted thawing groups, respectively. Similar to the thiobarbituric acid values, no significant difference was observed between the 0, 1, and 2 kV/cm PEF-assisted thawing groups, while the 4 kV/cm PEF-assisted thawing group exhibited the highest carbonyl value.

3.6. Effect of PEF-assisted thawing on the primary protein structure in Zhijiang duck meat

As shown in Fig. 3(A), the total sulfhydryl acid values were 2.54 ± 0.025, 2.49 ± 0.050, 2.40 ± 0.020, 1.97 ± 0.050 and 0.93 ± 0.090 in the 0, 1, 2, 3 and 4 kV/cm PEF-assisted thawing groups, respectively. The content of the total sulfhydryl group in the control group was the highest. No significant difference was observed in total sulfhydryl content between the 1 and 2 kV/cm PEF-assisted thawing groups. The total sulfhydryl acid values in the 4 kV/cm PEF-assisted thawing group were the lowest. This result indicated that the 2 kV/cm PEF-assisted thawing did not change the protein primary structure in zhijiang duck meat. The effect of different electric field intensities on the secondary structure of MP in zhijiang duck breast was shown in Fig. 3 (B). It is generally believed that, the higher the relative ratio of α-helixes, the more stable the protein structure is. The larger the relative proportion of β-sheets and random coils, the looser the protein structure(Z. Zhang et al., 2017). Our data showed that the proportion of α-helixes were 30.97 %, 35.97 %, 60.87 %, 56.89 % and 37.87 % in the 0, 1, 2, 3 or 4 kV/cm PEF-assisted thawing groups, respectively. α-helixes content was 66.91 %, showing the highest value in the control group. The content of α-helixes and β-sheet in the 0 kV/cm PEF-assisted thawing groups were lower than that of the PEF-assisted thawing treatment groups. This indicated that the secondary structure of the protein was damaged after the duck meats being thawed. The α-helix content was the highest in PEF-assisted thawing at 2 kV/cm group, which showed closest to the control. Our data showed that 2 kV/cm PEF-assisted thawing can maintain the structure of frozen duck breast.

3.7. Effect of PEF-assisted thawing on muscle fibre structure in Zhijiang duck meat

The sample in control presented tight and well-organized muscle fibres. In contrast, the muscle fibres in the 0 kV/cm PEF-assisted thawing group showed significant ice crystal formation and structural damage. However, the 1, 2, and 3 kV/cm PEF-assisted thawing groups exhibited smaller, more uniform ice crystals and narrower gaps between muscle fibres (Fig. 4A). These results indicated that the 2 kV/cm PEF-assisted thawing group better preserved the structural integrity of zhijiang duck meat.

As shown in Fig. 4B, changes in the microstructure of duck meat were observed by SEM; the observation surface selected by SEM was the cross section of myofibrils. The muscle fibres in control were arranged tightly and orderly, with no obvious gaps observed between muscle fibre bundles. Large voids appeared in the microstructure of the 0 kV/cm PEF-assisted thawing group. In the 2 kV/cm PEF-assisted thawing group,

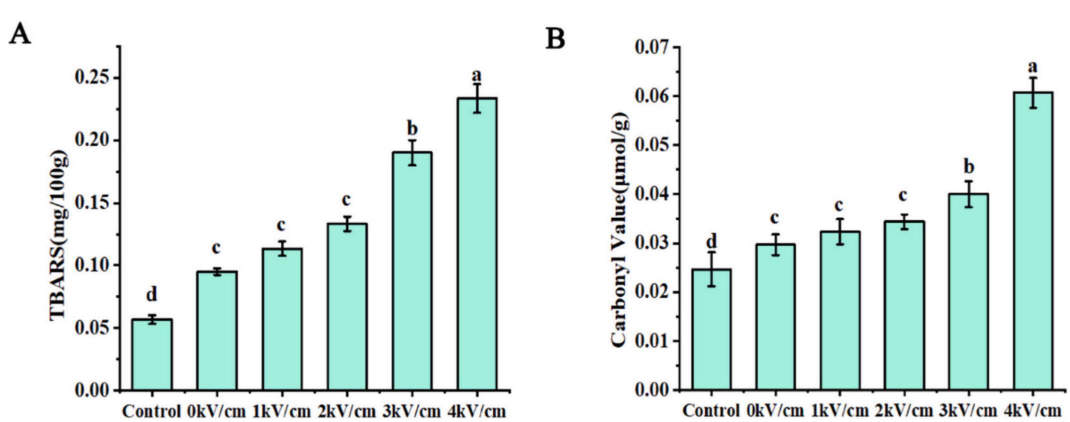

Fig. 2. Effect of PEF treatment on the fat and protein oxidation in duck breast meat. (A) The thiobarbituric acid values in duck breast meats were tested after being treated with 0,1,2,3 and 4 kV/cm PEF (B) The carbonyl value in duck breast meats after being treated with 0,1,2,3 and 4 kV/cm PEF. The freshed duck meats were use as control. Different lowercase letters indicated $P < 0.05$. The fresh meats were used as control. Each group has at least 5–8 replicates.

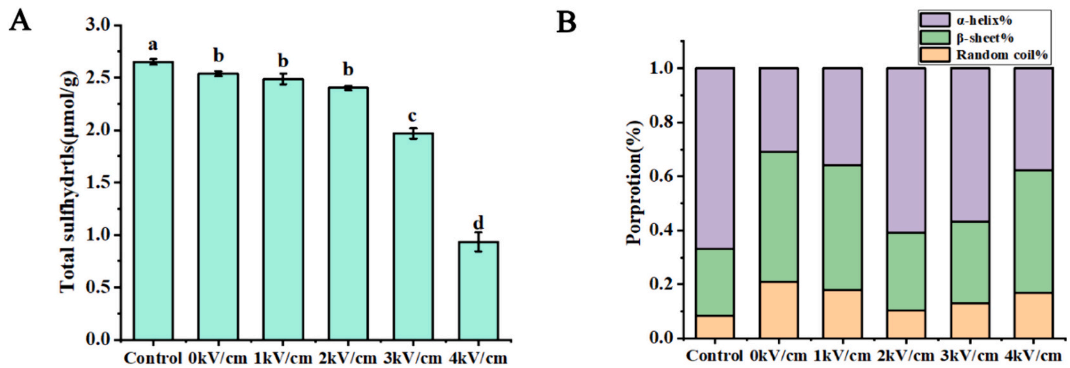

Fig. 3. Effect of PEF treatment on protein structure of duck breast meat. (A)The total sulfhydryl groups in PEF-assisted thawing zhijiang duck meats were tested after being treated with 0,1,2,3 and 4 kV/cm PEF. (B) The protein secondary structure of the PEF-assisted thawing zhijiang duck meats were tested after the meats being treated with 0,1,2,3 and 4 kV/cm PEF. The fresh meats were used as control. Each group has at least 5–8 replicates.

the myofibril arrangement was tightly ordered, the outline was clear, and no obvious gap was observed between the muscle fibre bundles. The structure of the 4 kV/cm PEF-assisted thawing group was the coarsest, the degree of separation between muscle fibres sharply increased, the tissue became looser, and evident cracks appeared. The results showed that the 2 kV/cm PEF-assisted thawing group could better maintain the microstructure of zhijiang duck meat.

4. Discussion

Thawing can lead to a significant decrease in the quality of frozen meat, mainly due to microbial infection, myosin denaturation, lipid oxidation, and lipid protein cross-linking, which causes the aggregation of myofibrillar proteins and reduces the water-holding capacity of muscle proteins(Guo et al., 2021; Sriket, Benjakul, Visessanguan, & Kijroongroiana, 2007; Zhou, Zhang, & Xu, 2012). Electric field-assisted thawing technology can reduce this degree of deterioration due to the use of an electric field on the meat products and accelerate the thawing rate of frozen meat(Lv, Song, Wang, Ruan, & Geng, 2019). In this study, we reported that pulse electric field-assisted thawing increased the thawing rate of zhijiang duck meat. Research has shown that using PEF-assisted thawing can shorten thawing time and improve the quality of meat. Some studies also emphasize that PEF-assisted thawing can increase the thawing rate of pork, beef, chicken and tuna(Bai, Huo, & Fan, 2017; X. L. He, Liu, Nirasawa, Zheng, & Liu, 2013; X. L. He, Liu, Tatsumi, Nirasawa, & Liu, 2014).

The method of thawing at room temperature takes the longest time, resulting in poor water retention of meat and severe oxidation of lipids and proteins. Refrigeration thawing takes a long time, but the original quality of food is basically maintained due to the inability of microorganisms to reproduce at low temperatures. However, refrigerated thawing can significantly reduce indicators such as thawing loss, cooking loss, and myoglobin content, while the degree of microstructure damage is relatively small. Hydrolyzed freezing, with a fast thawing speed, may lead to a decrease in food quality(Yuan et al., 2020). Ultrasonic thawing is a physical thawing method that significantly improves the thawing rate of squid and reduces protein denaturation and oxidation(Wu et al., 2022). The internal juice of the meat cannot fully return to the cells and resulting in a large amount of nutrient loss. The microwave thawing shows fast speed hawing, but it has a significant impact on the nutrition and taste of the food itself, which can easily cause external ripening and internal coldness(Kutlu et al., 2022). Radio frequency thawing is an electromagnetic field heating method that has faster thawing speed and better temperature uniformity(Llave & Erdogdu, 2022). Radio frequency thawing also has the advantages of energy conservation and easy control, maximizing the quality of thawed meats(Llave et al., 2022). High voltage electrostatic field thawing is a method that can significantly shorten the thawing time, reduce juice loss rate, minimize damage to the microstructure of beef, and reduce thawing and cooking losses(Dalvi-Isfahan, Hamdami, Le-Bail, & Xanthakis, 2016).

PEF is a new non-thermal processing technology for food with the advantages of being fast and efficient, having low power consumption, and producing low pollution. It has been reported that PEF treatment increases the degradation of proteins, such as troponin and tropomyosin in duck meat, impairs the structure of the meat, increases membrane permeability to allow calcium ions to be released from the organelles, and hinders the binding of actin and myosin or causes physical damage to some sarcomere proteins(Lung et al., 2022). It results in an improvement in hardness, chewiness, and tenderness(Lung et al., 2022). The uniqueness of zhijiang duck lies in its unique origin, mainly derived from the special climatic conditions in the zhijiang region. In autumn and winter, there are differences in temperature, humidity, and wind speed between zhijiang and other neighboring counties and cities, which makes the zhijiang Duck produced unique and distinctive in flavor. Its meat quality is a major highlight of zhijiang duck, with tender, firm, and crispy texture, as well as low fat content, preserving the original flavor of duck meat. This unique meat quality characteristic makes zhijiang duck stand out in terms of taste and become the first choice for food enthusiasts. Here, we reported that PEF-assisted thawing can not only improve the thawing rate of zhijiang duck meat but also improve its hardness, chewiness, and tenderness. Our data also showed that PEF-assisted thawing could inhibit the transition from bound water and bound water to free water. Some studies reported that PEF could also inhibit the denaturation of myofibrillar proteins caused by ice crystal peak compression and protect the structure of muscle fibres, which permit a good water holding capacity of zhijiang duck meat. Additionally, the mechanisms need to be explored.

5. Conclusion

In this study, the effects of pulse electric field-assisted thawing with different electric field intensities on the thawing time, color, texture, shear force, protein secondary structure, and myofibril structure of zhijiang duck meat were elucidated. Our results indicated that PEF-assisted thawing could improve the quality of zhijiang duck meat, which will provide a reference for the application of PEF-assisted thawing on the market.

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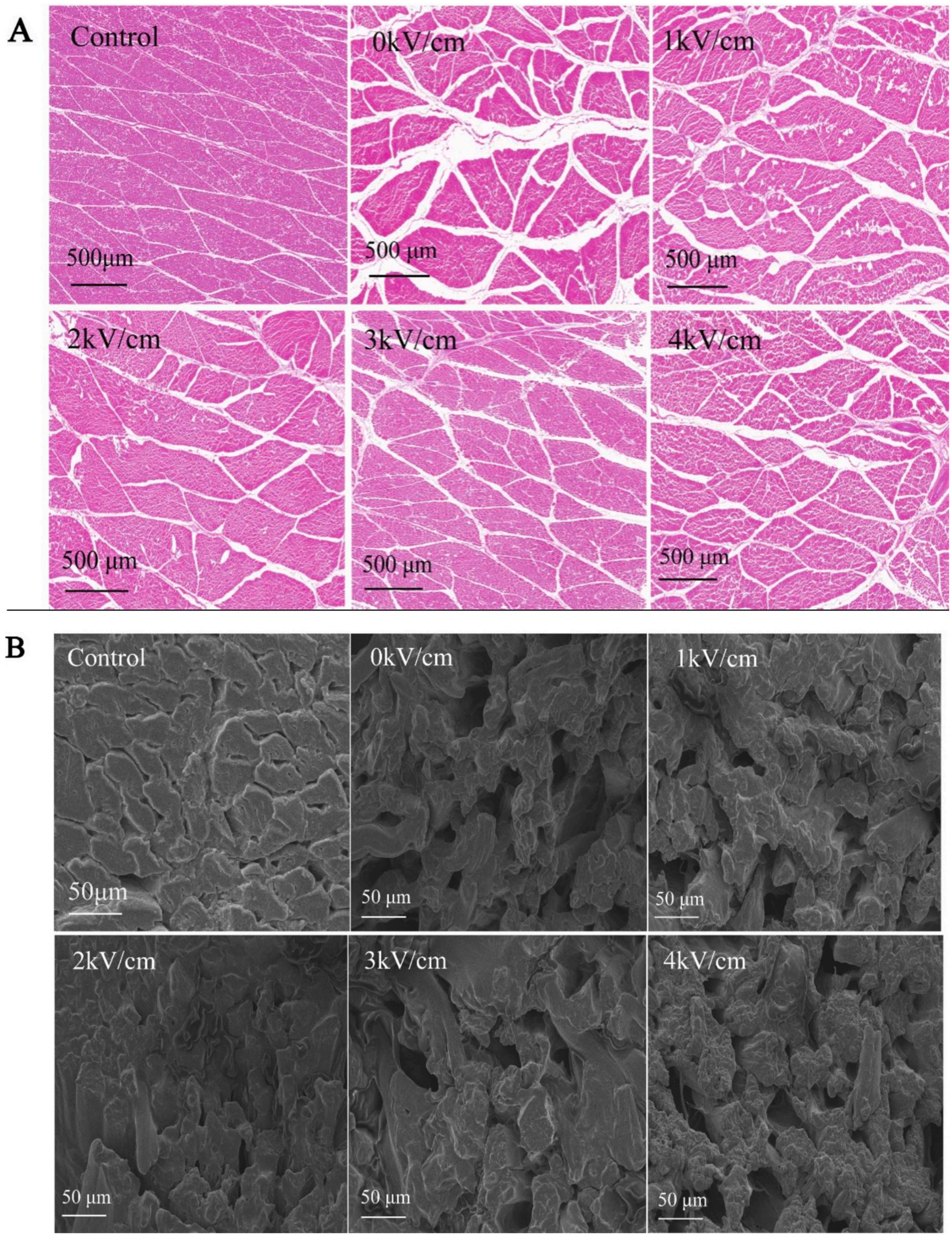

Fig. 4. Effect of PEF treatment on the structure of duck muscle fibril. (A) The duck meats were treated with 0,1,2,3 and 4 kV/cm PEF. Then, the duck breast meats were stained with hematoxylin and the structure of muscle fibrils were imaged by microscopy. Scale bar: 500 μm. (B) The duck meats were treated with 0,1,2,3 and 4 kV/cm PEF. Then, the duck breast meats were stained with hematoxylin and the structure of muscle fibrils were imaged by scanning electron microscopy (SEM). Scale bar: 500 μm. The fresh meats were use as control. Each group has at least 5–8 replicates.

CRediT authorship contribution statement

Yanyang Wu: Writing – review & editing, Supervision, Data curation, Writing – original draft. **Yan Xu:** Writing – review & editing, Writing – original draft. **Qingwu Shen:** Project administration, Funding acquisition. **Tingxia Xu:** Formal analysis, Data curation. **Zhuoqi Dong:** Methodology, Investigation. **Aihua Lou:** Funding acquisition.

Declaration of competing interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Data availability

Data will be made available on request.

References

Alvarenga, T., Hopkins, D. L., Ramos, E. M., Almeida, A. K., & Geesink, G. (2019). Ageing-freezing/thaw process affects blooming time and myoglobin forms of lamb meat during retail display. *Meat Science, 153*, 19–25. https://doi.org/10.1016/j.meatsci.2019.02.016

Arroyo, C., Eslami, S., Brunton, N. P., Arimi, J. M., Noci, F., & Lyng, J. G. (2015). An assessment of the impact of pulsed electric fields processing factors on oxidation, color, texture, and sensory attributes of Turkey breast meat. *Poultry Science, 94*(5), 1088–1095. https://doi.org/10.3382/ps/pev097

Astrain-Redin, L., Raso, J., Cebrian, G., & Alvarez, I. (2019). Potential of pulsed electric fields for the preparation of Spanish dry-cured sausages. *Scientific Reports, 9*(1), 16042. https://doi.org/10.1038/s41598-019-52464-3

Bai, Y. X., Huo, Y., & Fan, X. J. (2017). Experiment of thawing shrimps (Penaeus vannamei) with high voltage electric field. *International Journal of Applied Electromagnetics and Mechanics, 55*(3), 499–506. https://doi.org/10.3233/Jae-170020

Bhat, Z. F., Morton, J. D., Mason, S. L., & Bekhit, A. E. A. (2019). Current and future prospects for the use of pulsed electric field in the meat industry. *Critical Reviews in Food Science and Nutrition, 59*(10), 1660–1674. https://doi.org/10.1080/10408398.2018.1425825

Cai, L., Cao, M., Regenstein, J., & Cao, A. (2019). Recent advances in food thawing technologies. *Comprehensive Reviews in Food Science and Food Safety, 18*(4), 953–970. https://doi.org/10.1111/1541-4337.12458

Cai, L., Zhang, W., Cao, A., & Cao, M. (2020). Effects of different thawing methods on the quality of largemouth bass (Micropterus salmonides). *LWT-Food Science and Technologies, 120*, Article 108908. https://doi.org/10.1016/j.lwt.2019.108908

Cao, M., Cao, A., Wang, J., Cai, L., Regenstein, J., Ruan, Y., & Li, X. (2018). Effect of magnetic nanoparticles plus microwave or far-infrared thawing on protein conformation changes and moisture migration of red seabream (Pagrus Major) fillets. *Food Chemisty, 266*, 498–507. https://doi.org/10.1016/j.foodchem.2018.06.057

Dalvi-Isfahan, M., Hamdami, N., Le-Bail, A., & Xanthakis, E. (2016). The principles of high voltage electric field and its application in food processing: A review. *Food Research International, 89*, 48–62. https://doi.org/10.1016/j.foodres.2016.09.002

Eastridge, J. S., & Bowker, B. C. (2011). Effect of rapid thawing on the meat quality attributes of USDA select beef strip loin steaks. *Journal of Food Science, 76*(2), S156–S162. https://doi.org/10.1111/j.1750-3841.2010.02037.x

Ersoy, B., Aksan, E., & Ozeren, A. (2008). The effect of thawing methods on the quality of eels (Anguilla anguilla). *Food Chemistry, 111*(2), 377–380. https://doi.org/10.1016/j.foodchem.2008.03.081

Guo, Z., Ge, X., Yang, L., Ma, G., Ma, J., Yu, Q. L., & Han, L. (2021). Ultrasound-assisted thawing of frozen white yak meat: Effects on thawing rate, meat quality, nutrients, and microstructure. *Ultrasonics Sonochemistry, 70*, Article 105345. https://doi.org/10.1016/j.ultsonch.2020.105345

He, X. L., Liu, R., Nirasawa, S., Zheng, D. J., & Liu, H. J. (2013). Effect of high voltage electrostatic field treatment on thawing characteristics and post-thawing quality of frozen pork tenderloin meat. *Journal of Food Engineering, 115*(2), 245–250. https://doi.org/10.1016/j.jfoodeng.2012.10.023

He, X. L., Liu, R., Tatsumi, E., Nirasawa, S., & Liu, H. J. (2014). Factors affecting the thawing characteristics and energy consumption of frozen pork tenderloin meat using high-voltage electrostatic field. *Innovative Food Science & Emerging Technologies, 22*, 110–115. https://doi.org/10.1016/j.ifset.2013.12.019

He, Y., Zhang, C., Zheng, Y., Xiong, H., Ai, C., Cao, H., & Teng, H. (2023). Effects of blackberry polysaccharide on the quality improvement of boiled chicken breast. *Food Chemistry: X, 18*, Article 100623. https://doi.org/10.1016/j.fochx.2023.100623

Hsieh, C. W., Lai, C. H., Ho, W. J., Huang, S. C., & Ko, W. C. (2010). Effect of thawing and cold storage on frozen chicken thigh meat quality by high-voltage electrostatic field. *Journal of Food Science, 75*(4), M193–M197. https://doi.org/10.1111/j.1750-3841.2010.01594.x

Hu, F., Qian, S., Huang, F., Han, D., Li, X., & Zhang, C. (2021). Combined impacts of low voltage electrostatic field and high humidity assisted-thawing on quality of pork steaks. *LWT-Food Science and Technologies, 150*, Article 111987. https://doi.org/10.1016/j.lwt.2021.111987

Jia, G., Sha, K., Meng, J., & Liu, H. (2019). Effect of high voltage electrostatic field treatment on thawing characteristics and post-thawing quality of lightly salted, frozen pork tenderloin. *LWT-Food Science and Technologies, 99*, 268–275. https://doi.org/10.1016/j.lwt.2018.09.064

Kantono, K., Hamid, N., Ma, Q., Oey, I., & Farouk, M. (2021). Changes in the physicochemical properties of chilled and frozen-thawed lamb cuts subjected to pulsed electric field processing. *Food Research International, 141*, Article 110092. https://doi.org/10.1016/j.foodres.2020.110092

Kutlu, N., Pandiselvam, R., Saka, I., Kamiloglu, A., Sahni, P., & Kothakota, A. (2022). Impact of different microwave treatments on food texture. *Journal of Texture Studies, 53*(6), 709–736. https://doi.org/10.1111/jtxs.12635

Leygonie, C., Britz, T. J., & Hoffman, L. C. (2011). Protein and lipid oxidative stability of fresh ostrich M. Iliofibularis packaged under different modified atmospheric packaging conditions. *Food Chemistry, 127*(4), 1659–1667. https://doi.org/10.1016/j.foodchem.2011.02.033

Llave, Y., & Erdogdu, F. (2022). Radio frequency processing and recent advances on thawing and tempering of frozen food products. *Critical Reviews in Food Science and Nutrition, 62*(3), 598–618. https://doi.org/10.1080/10408398.2020.1823815

Lung, C. T., Chang, C. K., Cheng, F. C., Hou, C. Y., Chen, M. H., Santoso, S. P., & Hsieh, C. W. (2022). Effects of pulsed electric field-assisted thawing on the characteristics and quality of Pekin duck meat. *Food Chemistry, 390*. doi:ARTN 13313710.1016/j.foodchem.2022.133137.

Lv, F. C., Song, J. X., Wang, P., Ruan, H. O., & Geng, J. H. (2019). Influencing factors of flow field of ionic wind induced by Corona discharge in a multi-needle-to-net electrode structure under direct-current voltage. *IEEE Access, 7*, 123671–123678. https://doi.org/10.1109/Access.2019.2938420

Moselhy, A. A. A., & Hady, E. (2019). Gross, histochemical and electron microscopical characterization of the Pecten oculi of Baladi ducks (Anas boschas domesticus). *Journal of advanced veterinary and animal Research, 6*(4), 456–462. https://doi.org/10.5455/javar.2019.f368

Sriket, P., Benjakul, S., Visessanguan, W., & Kijroongroiana, K. (2007). Comparative studies on the effect of the freeze-thawing process on the physicochemical properties and microstructures of black tiger shrimp and white shrimp muscle. *Food Chemistry, 104*(1), 113–121. https://doi.org/10.1016/j.foodchem.2006.11.004

Tarana, A., Saiful, I. M., Najmul, H., Linzy, E., Badrul, H., Mohammad, N., … Kabir, L. (2023). Phenotypic and genotypic characteristics of antimicrobial resistance in Citrobacter freundii isolated from domestic ducks (Anas platyrhynchos domesticus) in Bangladesh. *Antibiotics (Basel), 12*(4), 769. https://doi.org/10.3390/antibiotics12040769

Wu, B. A., Qiu, C. C., Guo, Y. T., Zhang, C. H., Guo, X. Y., Bouhile, Y., & Ma, H. L. (2022). Ultrasonic-assisted flowing water thawing of frozen beef with different frequency modes: Effects on thawing efficiency, quality characteristics and microstructure. *Food Research International, 157*, Article 111484. doi:ARTN 11148410.1016/j.foodres.2022.111484.

Xia, X., Kong, B., Liu, J., Diao, X., & Liu, Q. (2012). Influence of different thawing methods on physicochemical changes and protein oxidation of porcine longissimus muscle. *LWT - Food Science and Technology, 46*(1), 280–286. https://doi.org/10.1016/j.lwt.2011.09.018

Xie, Y., Chen, B., Guo, J., Nie, W., Zhou, H., Li, P., & Xu, B. (2021). Effects of low voltage electrostatic field on the microstructural damage and protein structural changes in prepared beef steak during the freezing process. *Meat Science, 179*, Article 108527. https://doi.org/10.1016/j.meatsci.2021.108527

Yuan, J., Li, H., Tao, W. L., Han, Q., Dong, H. Q., Zhang, J., & Xu, T. T. (2020). An effective method for extracting anthocyanins from blueberry based on freeze-ultrasonic thawing technology. *Ultrasonics Sonochemistry, 68*, Article 105192. . doi: ARTN 10519210.1016/j.ultsonch.2020.105192.

Zhang, S., Sun, L., Ju, H., Bao, Z., Zeng, X.-a., & Lin, S. (2021). Research advances and application of pulsed electric field on proteins and peptides in food. Food Research International, 139, 109914. doi:https://doi.org/10.1016/j.foodres.2020.109914.

Zhang, Y., Bao, Q., Cao, Z., Bian, Y., Chen, G., & Xu, Q. (2023). Chinese domestic ducks evolved from mallard duck (Anas platyrhynchos) and spot-billed duck (a. zonorhyncha). *Animals(Basel), 13*(7), 1156. https://doi.org/10.3390/ani13071156

Zhang, Z., Yang, Y., Zhou, P., Zhang, X., & Wang, J. (2017). Effects of high pressure modification on conformation and gelation properties of myofibrillar protein. *Food Chemisty, 217*, 678–686. https://doi.org/10.1016/j.foodchem.2016.09.040

Zhou, G. H., Zhang, W. G., & Xu, X. L. (2012). China's meat industry revolution: Challenges and opportunities for the future. *Meat Science, 92*(3), 188–196. https://doi.org/10.1016/j.meatsci.2012.04.016